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Title: **NEW GROUND AND SPACE-BASED GPS TRACKING TECHNIQUES FOR HIGH-EARTH AND DEEP SPACE ORBIT DETERMINATION APPLICATIONS**

Authors: (all at **Jet Propulsion Laboratory, California Institute of Technology)**

Dr. Stephen M. Lichten
Dr. Dennis Sweeney
Dr. Lawrence E. Young
Dr. Bruce J. Haines
Mr. Don J. Spitzmesser
Mr. Jeffrey M. Srinivasan
Dr. Charles E. Dunn
Dr. Sumita Nandi

BIOGRAPHIES

Dr. Stephen M, Lichten received an A.B. degree from Harvard University in astrophysics in 1978 and his Ph.D. from the California Institute of Technology in 1983 (also in Astrophysics). He has worked at the Jet Propulsion Laboratory (JPL) since the summer of 1983 and presently is the Group Supervisor of the Earth Orbiter Systems Group and a manager in the NASA Deep Space Network Advanced Systems Program. He has focused his efforts recently on high-accuracy satellite. orbit determination applications, emphasizing precise GPS tracking. As part of the GPS flight experiment on Topex/Poseidon, his group recently developed a capability for routine orbit determination accurate to better than 3 cm in altitude for Topex

Dr. Dennis Sweeney

Dr. Larry Young received his Ph.D. in Nuclear Physics from the. State University of New York at Stony Brook in 1975, and has worked at JPL since 1978, currently as a technical group supervisor working on the development of high precision radio interferometric techniques for spacecraft navigation and geodesy. He led the development of various techniques to reduce, instrumental errors in VLBI measurements, and to demonstrate nanosecond level clock synchronization with both VLBI and GPS. He has worked on the design and development of several high precision GPS receivers, and on novel applications of precision GPS to problems of scientific interest, He has initiated work on custom GaAs chip design to enable improved radiometric performance, and has worked with system studies aimed toward improving the performance of spacecraft ranging systems.

Dr. Bruce Haines received his Ph.D. in Aerospace Engineering Sciences from the University of Colorado in 1991, after which he joined the Earth Orbiter Systems Group at JPL. He is a member of the Topex/Poseidon Joint Verification and Precision Orbit Determination learns, and specializes in precise orbit and geodetic analyses using GPS and in oceanographic applications of satellite altimetry.

Mr. Don Spitzmesser

Mt. Jeffrey M. Srinivasan received the Bachelor of Arts in Engineering and Applied Sciences degree with honors from Harvard University in 1983 and the Master of Science in Electrical Engineering degree from University of Southern California in 1988. He joined the technical staff at the Jet Propulsion Laboratory in 1983. He is currently a Technical Group Leader and has been the lead hardware/software engineer on the Rogue/TurboRogue GPS receiver projects. He has designed custom digital integrated circuits (ICs) and developed of signal processing algorithms for GPS applications. He is currently adapting of the acquisition algorithms and system software of the TurboRogue GPS receiver for various GPS and non-GPS applications.

Dr. Charles E. Dunn received his Ph.D. in physics from Cornell University, in 1990, specializing in theoretical particle physics. In that year, he joined the GPS Systems Group at J]']. as a member of the Technical Staff. His main interests are GPS receiver development for ground and space applications and high accuracy applications of GPS.

Dr. Sumita Nandi received her BA from the University of Chicago in 1985 and her Ph.D. in particle physics from Cornell University in 199]. She is currently a Member of Technical Staff in the Earth Observations and Analysis Systems Section at JPL.

ABSTRACT

Satellites of the Global Positioning System (GPS) can be used to provide precise position and velocity information for receivers on the surface. of the Earth, in aircraft, or in low-Earth orbit, At altitudes above 5000 km, however, relatively few GPS satellites are visible. Yet GPS can still help provide a precise navigation and positioning capability, even for Earth orbiters at altitudes weii above the altitude of the downward broadcasting GPS satellites. in fact, GPS data can even play an important calibration role in interplanetary spacecraft navigation.

This paper discusses error analysis and field tests for use of GPS technology to provide orbit determination for satellites at altitudes of 40000-100000 km. An experiment being carried out by JPL in late 1993 and early 1994 will demonstrate how GPS-like tracking can help provide an operational orbit determination capability for geosynchronous satellites, such as TDRS. The field experiment for TDRS tracking utilizes 3 modified GPS ground receivers in a small (few-hundred km), local network. These receivers have been modified to track carrier phase from TDRS as well as carrier phase and pseudorange from GPS satellites. This new approach offers a low-cost alternative to more conventional tracking systems for geosynchronous satellites. For the TDRS demo, no new space hardware was needed, The goal for TDRS is 50-m near-real time accuracy.

For orbit accuracy at the few- meter level at altitudes up to 100000 km, a more global distribution of hybrid GPS receivers is needed for tracking the high-Earth orbiter and the GPS satellites simultaneously, although only a relatively small number of these special receivers is required. initial analysis of system performance indicates meter-level performance should be possible.

New deep space tracking applications of the Global Positioning System will also be discussed in this paper. They are essentially a variation on the high-Earth orbiter tracking technique using a ground GPS receiver which can track both GPS and non-GPS spacecraft. GPS ground receivers collocated with the deep space tracking antennas and refer-enced to the same oscillator can provide precise, continuous and timely calibrations for geodetic, atmospheric, and clock parameters which are critical to interplanetary navigation. The incorporation of GPS into **NASA's** Deep Space Network offers a number of significant performance, operational and economical advantages over systems currently in use to provide these calibration products.

INTRODUCTION

As originally conceived, the Global Positioning System (GPS) was designed to provide positioning accuracy at the several meter level for military real-time applications, innovative uses of GPS have been developed recently, however, which go far beyond the original expectations for GPS as a military navigation tool. Civilian and scientific uses of GPS have. led to a wide variety of applications in geodesy, surveying, navigation, and r-emote sensing, including a cm-level non-real time positioning capability for receivers on the surface of the Earth (Blewitt et al. **1992),** and several-cm accuracy for low-Earth satellite orbit determination (Yunck et al. 1993). Such high-precision applications typically require that high-quality clual-frequency GPS data from typically six or more relatively sophisticated receivers be combined and processed together in estimation software which incorporates detailed physical and observation models. Other less demanding needs can be met with simpler and inexpensive GPS receivers which provide 50-100 m position knowledge, Nearly all of these military and civilian GPS applications involve an upward- looking geometry where the users' receiving antennas are poi nted away from the Earth towards GPS satellites which are at higher altitude. Fig.1 shows an example of this geometry, with the low-Earth orbiter (Topex/Poseidon) and ground stations tracking GPS satellites. in this and most other positioning applications, the GPS receivers on the orbiter or on the ground are used with antennas with approximately hemispherical field of view looking away from the Earth.

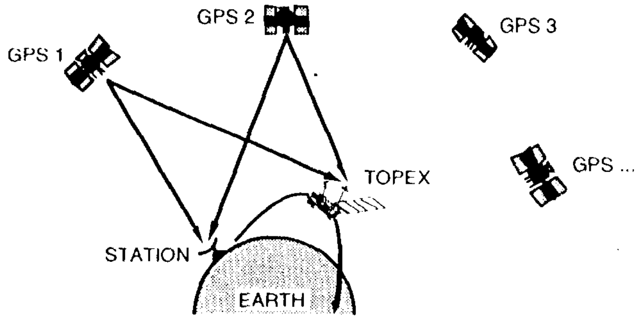
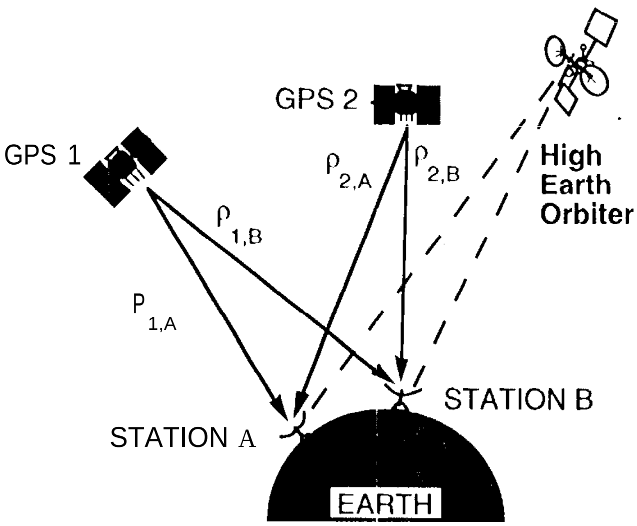


Fig. 1. Upwards looking geometry for low-Earth orbiter and ground stations tracking GPS satellites.

The Topex/Poseidon satellite carries an ocean altimeter which is being used to map the oceans' surfaces, measure global ocean circulation, and sense changes in ocean height. At its altitude --- slightly above 1300 km - 6-8 GPS satellites are typically in view at a given time with the upwards looking hemispherical field of view. At least 4 GPS satellites are required to enable a determination of the user position and clock relative to the GPS constellation. By relying at least partially on available precise dynamic models, a dynamical fit can be performed in a sequential filter using data over at least several hours and the accuracy of the solution improves significantly over that achieved from instant point solutions, Additional accuracy improvement results from differential elimination of the receiver and transmitter clocks at each measurement epoch. The differential solution also removes the effects of selective availability (SA), which is a clock dither on the GPS transmitters, While this requires common visibility of at least two GPS with at least two receivers (Fig. 1), such geometry is



range

range (phase) bias

clock offsets

$$\Phi_{1,A} = [\rho_{1,A} + B_{1,A} + C_1 + C_A]\, 2\pi/\lambda$$
$$\Phi_{1,B} = [\rho_{1,B} + B_{1,B} + C_1 + C_B]\, 2\pi/\lambda$$
$$\Phi_{2,A} = [\rho_{2,A} + B_{2,A} + C_2 + C_A]\, 2\pi/\lambda$$
$$\Phi_{2,B} = [\rho_{2,B} + B_{2,B} + C_2 + C_B]\, 2\pi/\lambda$$

$$(\Phi_{1,B} - \Phi_{1,A}) - (\Phi_{2,B} - \Phi_{2,A})$$
$$= [(\rho_{1,B} - \rho_{1A}) - (\rho_{2,B} - \rho_{2,A}) + B]\, 2\pi/\lambda$$

Fig. 3 Differential GPS tracking. Four simultaneous measurements of carrier phase (Φ) enable removal of transmitter and receiver clock offsets. After tracking for 12-24 hrs, the resultant linear combination of ranges enables estimation of GPS orbits to the level of a few tens of cm, and of ground coordinates to cm-level accuracy. The term B, in the final equation, is a composite bias term which is easily estimated from ~ 3 hrs of tracking. In GLT, the carrier phase from the high-Earth orbiter would also be included and its orbit similarly estimated.

Fig. 3 shows schematically how GLT relates to differential GPS tracking. This relationship is discussed at length in Lichten et al. (1993). In principle. this could be a powerful technique for orbit determination, since GPS orbit accuracy is routinely determined at several analysis centers to better than 50 cm, and the accuracy of the high-Earth satellite's orbit could, under ideal circumstances, approach that of the GPS satellites. Fig. 4 shows how overlapping data arcs of 30 hrs are used to assess orbit quality at the Jet Propulsion Laboratory. During a recent 1-week period in December 1993, for 25 GPS satellites the average rms overlap difference was 37 cm (RSS three-dimensional). During that week, the lowest rms was for PRN 22 (8 cm) while the highest rms was for PRN13 (109 cm).

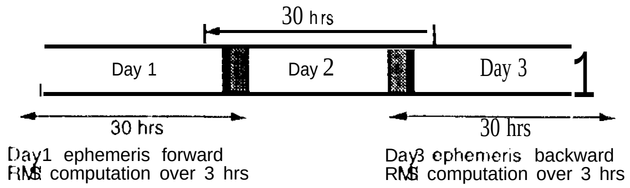


Fig. 4 Assessment of GPS orbit quality from daily GPS precise orbit determination at the Jet Propulsion Laboratory.

There are three possible GPS-compatible signals to consider: (1) an actual GPS L-band beacon; (2) a set of tones which can be tracked in a GPS ground receiver; and (3) the earlier phase from telemetry, tracked in a GPS receiver. Use of an actual GPS beacon (case 1) is probably not feasible due to possible interference with military operations. A suitably designed beacon (case 2), however, could transmit a set of tones at L-band which could be tracked in the GPS receiver with minor modifications. For example, a GPS receiver which ordinarily tracks 8 GPS satellites could be modified to track 7 GPS satellites and tones from one other satellite. With an adequate bandwidth separating the tones, ambiguities could be resolved anti a cm-level quality range measurement could be possible. Case 2 would in general require placing a new beacon on the user satellite. The third approach, tracking carrier phase from the user satellite, would be subject to any limitations on the availability crf the current carrier signals from the spacecraft. As in case 2, GPS ground receivers could be modified to enable simultaneous tracking of GPS anti the non-GPS signals. For either case 2 or 3, the beacon need not be at the GPS L-band frequency; a simple dowrrconversion to L-band would be used prior to feeding the non-GPS signal to the GPS ground receiver (Fig. 5).

in the next section, a covariance analysis will be presented to discuss the potential for case 2, where a beacon is placed on the user satellite to broadcast ranging tones. in the section following, an example of case 3 will be discussed - tracking geosynchronous TDRS satellites with small GPS ground terminals. An experiment for tracking TDRS with GPS ground receivers will be described. Three GPS receivers have been modified at JPL to enable reception of the Ku-band carrier phase from TDRS satellites (Fig. 5). The TDRS/GPS experiment began in iate January 1994. The use of GPS calibration measurements to support deep space navigation will aiso be explained, including description of a prototype system developed at JPL for providing such support for NASA interplanetary missions. Sample calibrations from the GPS tracking system will be shown and implications discussed. The final section of the paper summarizes the implications of the use of GPS for high-Earth and deep space applications.

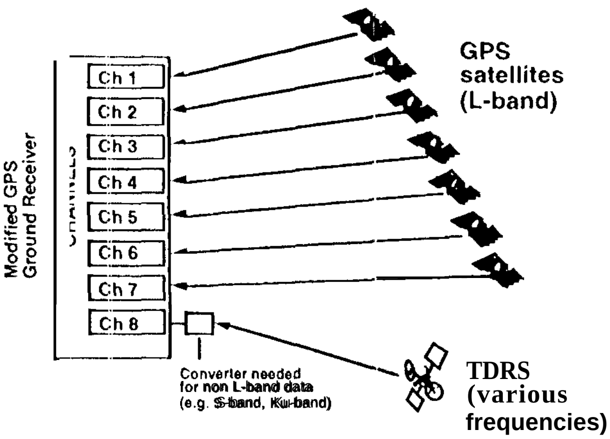


Fig. 5 Schematic for a modified GPS ground receiver to simultaneously track a high-Earth orbiter along with GPS satellites, For a satellite such as TDRS which broadcasts at frequencies outside the GPS L-band (1.2- 1.6 GHz), a small separate antenna with a downconverter would be added to the GPS ground instrument,

GPS-LIKE TRACKING: SPACECRAFT TONES

The use of small ground antennas and GPS receivers for tone-tracking of high-Earth/elliptical orbiters could potentially free up significant amounts of tracking time on larger and more expensive antennas ordinarily used to provide navigation and orbit determination, This is especially true at NASA's three deep space network (DSN) complexes, where tracking time is often scarce. The accuracy of the. combined high-Earth and GPS tracking system may also be superior to that available from other more conventional methods. POINTS (Precision Optical INTerferometer in Space) is an optical astrometric mission for identification and characterization of planetary systems around other stars in the solar neighborhood (Schumaker et al. 1991). This mission, presently in the planning stages, requires velocity determination to an accuracy of 0,5 mm/s (Ulvested 199?; Haines and Lichten 1992). Conventional NASA tracking systems are expected to result in orbit errors 1-2 orders of magnitude higher than this (Estefan 1991). However JPL's daily GPS orbit formal errors are at the level of O. 1 mm/s. If POINTS were to broadcast a suitable signal to be tracked in GPS ground receivers, the GPS-like tracking beacon scenario for the POINTS orbit determination problem might be a viable approach.

Table 2. Estimation Strategy {or GPS/POINTS analysis

Data Noise (30 minute observations)	
GPS earlier phase	1 cm
GPS P-code pseudorange	30 cm
POINTS: Ku-band beacon case	
pseudorange (tones)	5 cm
random noise over 1 min	
systematic measurement error	30 cm/12 hr
A-priori for estimated parameters	
POINTS position (X, Y, Z)	5 km
POINTS velocity (X, Y, Z)	50 m/s
GPS position (X, Y, Z)	100 m
GPS velocity (X, Y, Z)	1 m/s
GPS solar radiation pressure	25%
GPS y-bias	10^{-12} m/s^2
GPS carrier phase biases	1s
GPS/POINTS/station clock errors	1 s white noise
Zenith troposphere	40 cm a-priori +5 cm/$\sqrt{\text{day}}$ random walk
"Consider" parameters (not estimated, treated as systematic errors)	
POINTS solar radiation pressure	2 %
Polar motion (X, Y)	5 cm
Geocenter location (X, Y, Z)	5 cm
Earth rotation (UT 1- UTC)	0. 1 msec
Station locations (X, Y, Z)	1 cm
Earth gravitational constant	1 part per billion
Geopotential field (lumped)	25% GEM-10 - GEM-L2

A covariance analysis (see Lichten et al. 1993) was preformed for a nearly circular orbit at high altitude (100000 km). For a GPS-like beacon on the POINTS spacecraft, we assumed a series of tones would be broadcast at Ku-band with a 100 MHz bandwidth. These tones would be spaced so that an equivalent one-way range datatype would be produced with 5 cm data noise over 1 minute. averaging interval. A larger source of measurement noise results from electronic delays associated with the separate front end which would be attached to the GPS ground receivers (Fig. 5) to enable reception of the POINTS signals. We assumed that these delays would be slowly varying, and represented them in the filter as 1st order Gauss Markov process noise with amplitude 30 cm and 12-hr time constant. Each of the. six ground receivers would therefore be tracking up to 7 GPS satellites at once plus POINTS (instead of the usual 8 GPS satellites at once),

A simulated data set was fit over a 4-day interval (one POINTS orbital period). The estimation and filtering strategy was selected to be nearly identical to that used at

J]’], for actual GPS data processing, with the exception that POINTS was included as well. Table 2 shows assumptions of the analysis, which includes systematic error contributions from POINTS solar radial ion pressure mismodeling, Earth orientation, relative station locations, and gravity. Fig. 6 shows the expected orbit velocity and position errors for POINTS.

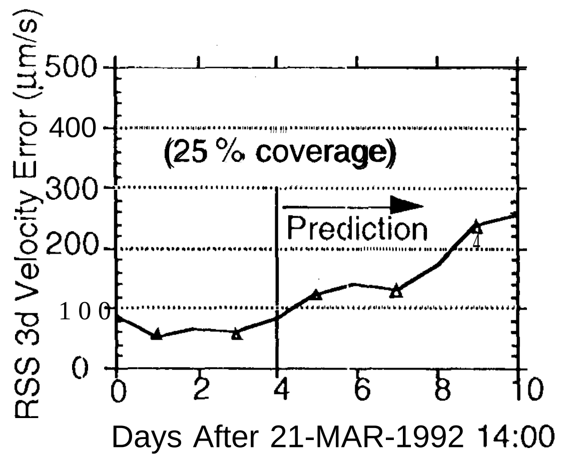


Fig. 6a. Orbit determination for POINTS with 6 ground sites and GI’S-like tracking. More than 80% of the orbit error is due to data noise and measurement coverage, with only small contributions from the systematic (consider) errors listed in Table 2. Velocity errors arc shown for tracking interval of slightly less than 4 days and also prediction interval of 6 days.

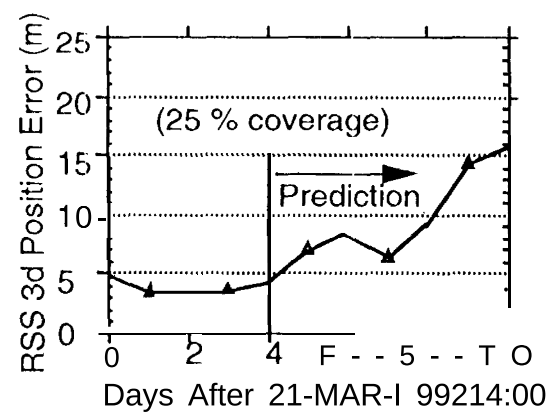


Fig. 6b. Position errors anticipated for POINTS corresponding to velocity errors in Fig. 6a.

Due to operational constraints of the POINTS mission, in this analysis, tracking was assumed to be available only 25% of the time. This limited tracking scenario accounts for the possibility that the spacecraft could be turned in such a way that the beacon would be pointing away from Earth, depending on where the astronomical sources were located in the sky**. Fig. 6 shows that the POINTS solution is robust and, based on our assumptions about capability to model forces on the satellite, can be predicted several days in advance without serious degradation of accuracy,

in summary, a high Earth orbiter (such as POINTS) can in principle be tracked to several-meter level position accuracy and velocity accuracy of O, 1mm/s if equipped with a GPS-like beacon at Ku-band and tracked from at least 6 modified GPS ground receivers which have been retrofitted so that the data from the high Earth et-biter and GPS satellites can be processed simultaneously. For frequencies other than Ku-band, performance may vary slightly since the ionosphere delay calibration from the GPS L1 and L2 signals will have some error and this will be more important at lower frequencies.

GPS-LIKE TRACKING: TDRS DEMONSTRATION

In late 1992, a preliminary study of new technologies for tracking geosynchronous satellites, specifically the Tracking and Data Relay Satellites (TDRS), was initiated at J}’], in the DSN Advanced Systems Program, at the request of the NASA sponsor (Haines et al. 1992; Nandi et al. 1992). At the conclusion of the study, NASA decided to sponsor a small demonstration experiment for tracking TDRS. The experiment utilizes three ground terminals, each of which includes a GPS TurboRogue ground receiver. These GPS receivers have been modified at JPL so that they can track 7 GPS (carrier phase and pseudorange) satellites + 1 TDRS (carrier phase) simultaneously (Fig. 5). Initially it was planned to deploy the three ground terminals within approximately 100 km of White Sands, New Mexico. The small network size is necessitated by the small TDRS footprint at White Sands, and offers a number of operational advantages as well. In most cases, carrier phase tracking would enable a complete orbit solution to be determined; however because TDRS satellites arc geostationary, carrier phase by itself provides a very weak determination of the longitude orbit component. A small amount of two-way range data (such data are regularly collected at White Sands) would be. adequate to determine the longitude orbital component provided the 2-way range data were precise enough. Fig. 7 includes a schematic of the experiment as originally conceived, and a plot showing anticipated orbit determination accuracy as a function of

** Since that analysis was completed, however, a new spacecraft design has been developed which allows for placement of two beacon transmitter antennas on opposite sides of the spacecraft so that coverage of the Earth is possible more than 75% of the time (ref).

two-way range precision, The eventual goal is to show that the system could meet a 50-m operational orbit determination requirement, with 2-hr delivery after a maneuver. In the context of the POINTS covariance analysis, it should be noted that if a geosynchronous satellite were equipped with the type of beacon assumed for POINTS, the expected orbit accuracy from a global tracking network from GLT would be about 3 m. In the case of TDRS, however, existing signal structure and the limited ground footprint put constraints on the performance. The expectation that only the earlier phase variations would be tracked in the GPS receivers (instead of ranging signals), and the small footprint near White Sands, are expected to lead to orbit determination about a factor of ten less accurate. The TDRS experiment was originally conceived as shown in Fig. 7; however, the actual baseline lengths are approximately 1000 km and 300 km, which should result in higher accuracy than for the case of 100x100 km.

There are a number of advantages to using GPS ground receivers in this type of tracking configuration, First, GPS receivers provide precise troposphere and ionosphere calibrations at each site, Second, GPS receivers provide cm-level ground site coordinates and global GPS tracking data enable other extremely accurate geodetic calibrations, inducting Earth orientation. Third, GPS ground receivers enable nanosecond-level inter-site clock time transfer so that precise measurement of differential carrier phase data can provide orbit determination even over relatively short baselines. Other advantages include the ease of maintenance of commercial GPS receivers and highly automated data processing systems already in place to handle data from GPS receivers. 10 JPL's routine processing system, retrieval of GPS data from nearly 50 sites worldwide is accomplished in about one-half a day; data processing and parameter estimation can take 6-12 hrs of time on a small (super-mini) computer. For a 3-station network dedicated to TDRS, total data processing time could be reduced to a few hrs provided that GPS orbital ephemerides were propagated forwards from the previous day's solution.

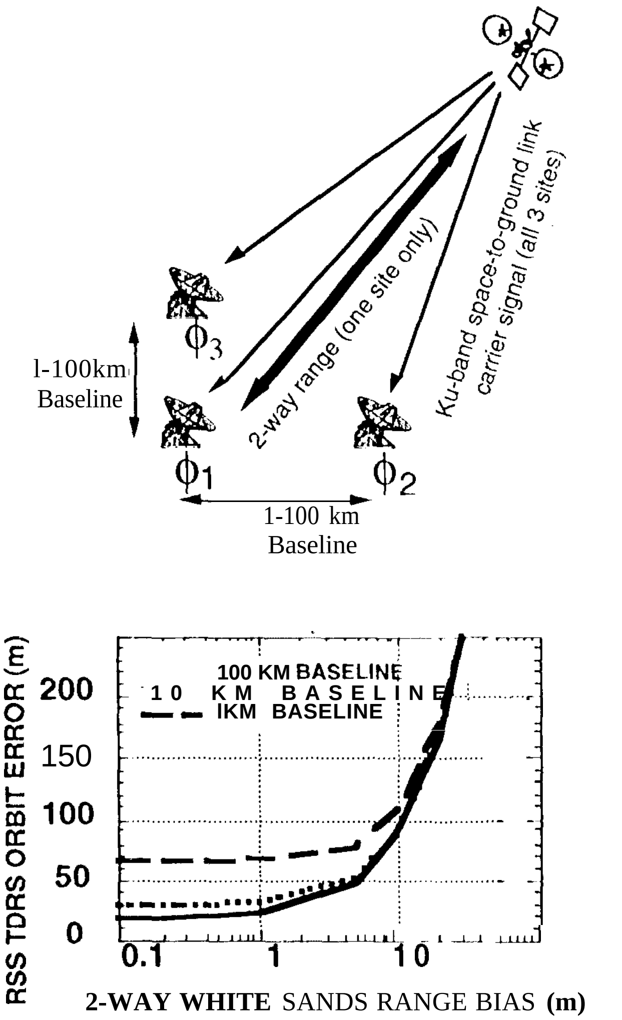


Fig. 7 Schematic of short-baseline tracking demo for TDRS using GPS ground receivers in local net.work. Expected orbit accuracy is shown in lower portion. Actual baselines in the demo are 300-1000 km.

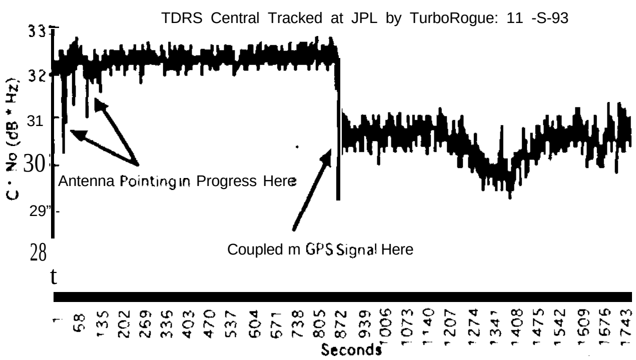


Fig. 8 initial detection of TDRS carrier phase at JPL with modified GPS receiver.

The present-day status of the TDRS/GPS demonstration experiment is that data collection was scheduled to take place between January 17-24 1994. One ground terminal was deployed at J]'l., which is well outside the TDRS footprint, after initial ground tests showed that the TDRS carrier phase could be easily tracked there since JPL happens to lie in the first sidelobe of the TDRS transmitter antenna pattern. The longer baseline to J} '1, should strengthen the orbit determination. Fig. 8 shows the initial detection of the TDRS earlier signal from the roof of a building at JPL with the GPS receiver. More detailed results and a complete discussion of the TDRS/GPS tracking, experiment will be presented in a future paper.

GPS DEEP SPACE TRACKING CAI,1 IIRA'I"1ONS

The role of ground (Earth) based GPS tracking in deep space (interplanetary) navigation can he envisioned as a logical extension of the use of GPS-like tracking for high-Earth satellite orbit determination. In the TDRS/GPS demo, a small horn antenna a few inches in diameter was used side by side with the usual GPS omni (hemispherical view) antenna, and the outputs of the two antennas are combined. For deep space tracking, a larger collection area is often needed, not only clue to the weakness of the signal, but also for the telemetry capacity. A GPS ground receiver could still be used in conjunction with the largest (70-meter) deep space tracking antennas. This, in fact, was done several years ago to track spacecraft at Venus. Several tone trackers based on GPS receiver boards are currently being used experimentally at two of the DSN stations, The more common situation, at least at the present time, however, has the deep space tracking system "separate from the GPS ground receiver, Nonetheless, co-location of the GPS ground receiver at the deep space tracking site provides nearly all the benefits of GLT when the GPS receiver is linked to the same clock and frequency standard (a hydrogen maser at the DSN sites) which is used for the deep space tracking. The main difference is that the time transfer is more difficult with deep space tracking case since all cable and electronic delays between the GPS ground terminal and the separate, larger (and more complicated) deep space tracking system must be calibrated. The geodetic and atmospheric calibrations from GPS are still available, and in fact assume even greater importance for deep space tracking cent-igurations.

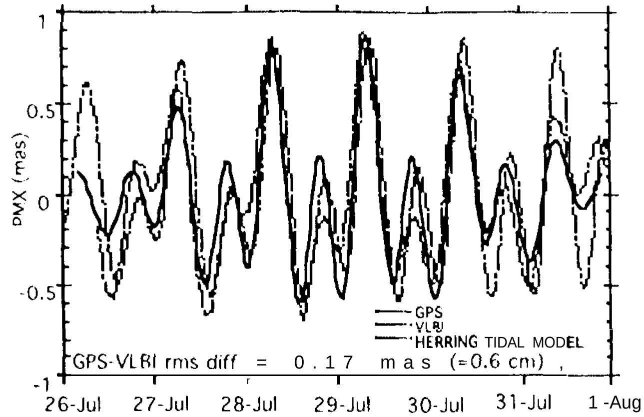


Fig. 9. GPS estimation of change in Earth's pole relative to the Earth's crust — polar motion — with high-resolution to show effects of oceanic tides (Dickey and Feissel 1994). The tidal effect is about 5 cm over a day and is confirmed to better than 1 cm with wry long baseline interferomet ry (VLBI), a radio telescope astrometric technique.

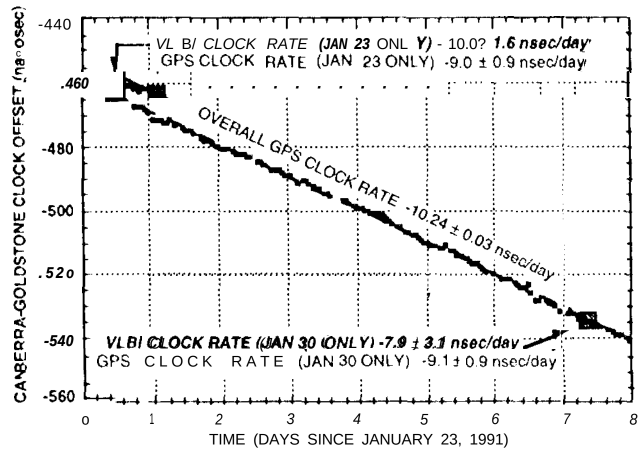


Fig. 10. High-accuracy relative clock measurements between two DSN sites in California and Australia from continuous GPS tracking. GPS measurements are accurate to better than 1 nsec/day, and individual clock offset estimates (every 5 min from GPS) show internal scatter of a few tenths of nsec.

A prototype GPS calibration system was developed at JPL which utilizes data from a global network of ground sites, The calibrations to be provided include: troposphere and ionosphere path delays; Earth rotation and polar motion variations; station coordinates; and time transfer. The accuracy goals for all these calibrations are at the few cm-level, with the exception of the clock sync for which 1 nscc is the target. Initial results from the prototype GPS calibration system are shown in Figs. 9-11. Wheo made operational, such a calibration system could eventually support a deep space navigation capability between 10 and 50 nanoradians angular accuracy, depending on the level of other systematic errors in the deep space data. The GPS-based calibration system is expected to be very valuable for the DSN since most of these calibrations are either presently determined less accurately when non-GPS techniques are employed, or (as in the case for Earth orientation) require scheduling of quasar observations with the largest (and most expensive) of the deep space antennas, thereby deer-casing available antenna time for tracking spacecraft,

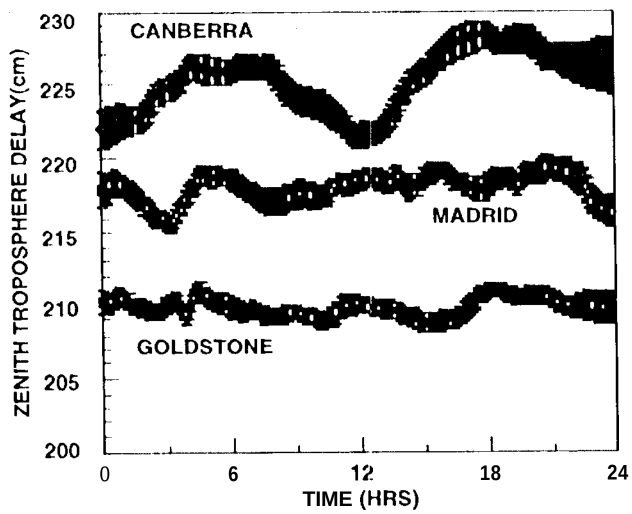


Fig. 11. Zenith troposphere delays at the 3 NASA DSN sites measured with GPS. Width of lines indicates precision of GPS estimates (+/- 1σ), better than 1 cm most of the time.

CONCLUSIONS

GPS-like tracking (GLT) offers a new way to track high-Earth and interplanetary spacecraft. GLT for Earth orbiters relies on a several ground GPS receivers which are modified to simultaneously track GPS satellites and one or more specific non-GPS satellites. Covariance analyses predict that even at 100000 km altitude, orbit accuracy of a few meters should be possible with GLT and an appropriate system design. A 1994 demonstration experiment for tracking TDRS differential carrier phase with ground GPS receivers is the first step towards development of a GLT system for geosynchronous orbiters. In the case of TDRS, 50-m accuracy is the goal; the accuracy is limited primarily by various constraints arising from the TDRS signal characteristics. For deep space applications, the GLT configuration may be modified to include a large deep space tracking antenna system. The advantages of incorporating, GPS ground observations for geodetic, clock, and atmospheric calibrations for deep space tracking are improved efficiency and better accuracy. A prototype G1'S-based calibration system for deep space tracking has shown that the. concept is indeed feasible.

ACKNOWLEDGMENT

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REFERENCES

Bertiger, W., Wu, S.C., Yunck, P.}'., Muellerschoen, R. J., Bar-Sever, Y., Davis, E. S., Lichten, S. M., Munson, T. N., and Willis, P., "Early Results from the Topex/Poseidon GPS Precise Orbit Determination Demonstration," AAS/AIAA Space Flight Mechanics Meeting, paper AAS 93-154, Feb. 22-24, 1993, Pasadena, CA.

Blewitt, G. Heflin, M. B., Webb, F.H., Lindqwister, U. J., anti Malla, R.P., "Global Coordinates with Centimeter Accuracy in the International Terrestrial Reference Frame Using [i}'S," *Geophys. Res. Lett.*, Vol. 19, 853-856, May 4, 1992.

Dickey, J., and Feissel, M. (eds.), "IERS Technical Note # 16: Results from the SEARCH'92 Campaign," 1994 (in press), Central Bureau of the IERS, 61 Avenue de l'Observatoire, F-75014, Paris, France.

Estefan, J. A., "Precise Orbit Determination of High-Earth Elliptical Orbiters Using Differenced Doppler and Range Measurements," *TDA Progress Report*, Vol. 42-106, Aug. 15, 1991, Jet Propulsion Laboratory, Pasadena, CA., pp. 1-22.

Haines, B. J., and Lichten, S.M. "POINTS Orbit Determination with GPS-Like Beacon, " JPL Internal Document (1OM 335.8-92-036), Dec. 8, 1992.

Haines, B. J., Lichten, S.M., Malla, R.P., and Wu, S.C. "Application of GPS Tracking Techniques to Orbit Determination of TDRSS," Flight Mechanics/Estimation Theory Symp., Greenbelt, MD, May 1992.

Lichten, S. M., Edwards, C. D., Young, L. E., Nandi, S., Dunn, C., and Haines, B. J., "A demonstration of TDRS orbit determination using differential tracking observable from GPS ground receivers,'" AAS/AIAA Space Flight Mechanics Conference AAS Paper 93-160, Pasadena CA, February, 1993.

Nandi, S., Edwards, C.D., and Wu, S.C., "TDRSS Orbit Determination Using Short Baseline Differenced Carrier Phase," Flight Mechanics/Estimation Theory Symp., Greenbelt, MD, May 1992.

Schumaker, B. et al., 'The POINTS Instrument for TOPS: 1991 Progress Report, JPL Internal Document, 233 pp., Nov. 12, 1991.

Ulvestad, J. "POINTS orbit determination requirements," JPL Internal Document, July 6, 1992.

Wu, S.C., "Differential GPS Approaches to Orbit Determination of High-Altitude Earth Satellites," AAS/AIAA Astrodynamics conference, paper AAS 85-430, Aug. 12-15, 1985, Vail, CO.

Yunck, T. P., Bertiger, W. I., Wu, S. C., Bar-Sever, Y., Christensen, E. J., Haines, B. J., Lichten, S. M., Muellerschoen, R. J., Vigue, Y., and Willis, P., "First Assessment of GPS-Based Reduced Dynamic Orbit Determination on TOPEX/POSEIDON," *Geophys. Res. Lett.*, 1993 (in press).